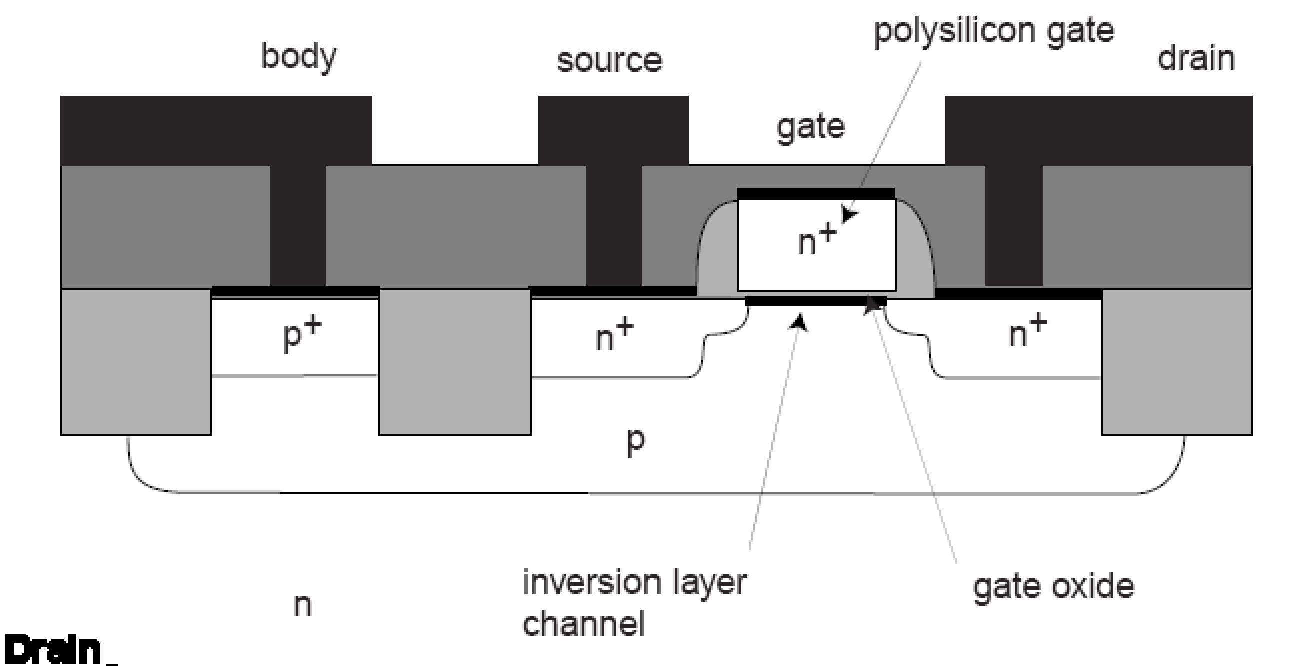
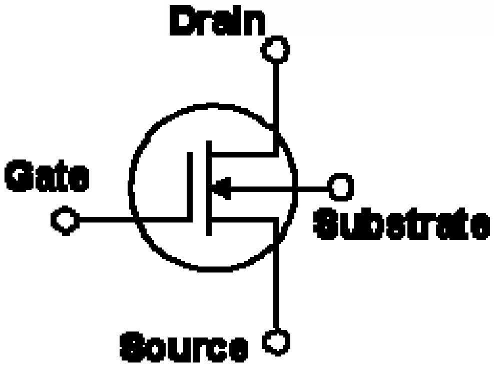
MOSFETs

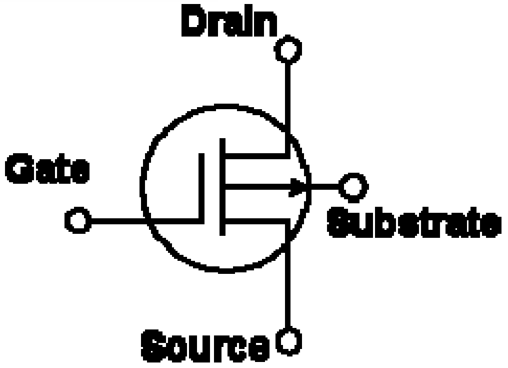
MOSFETs





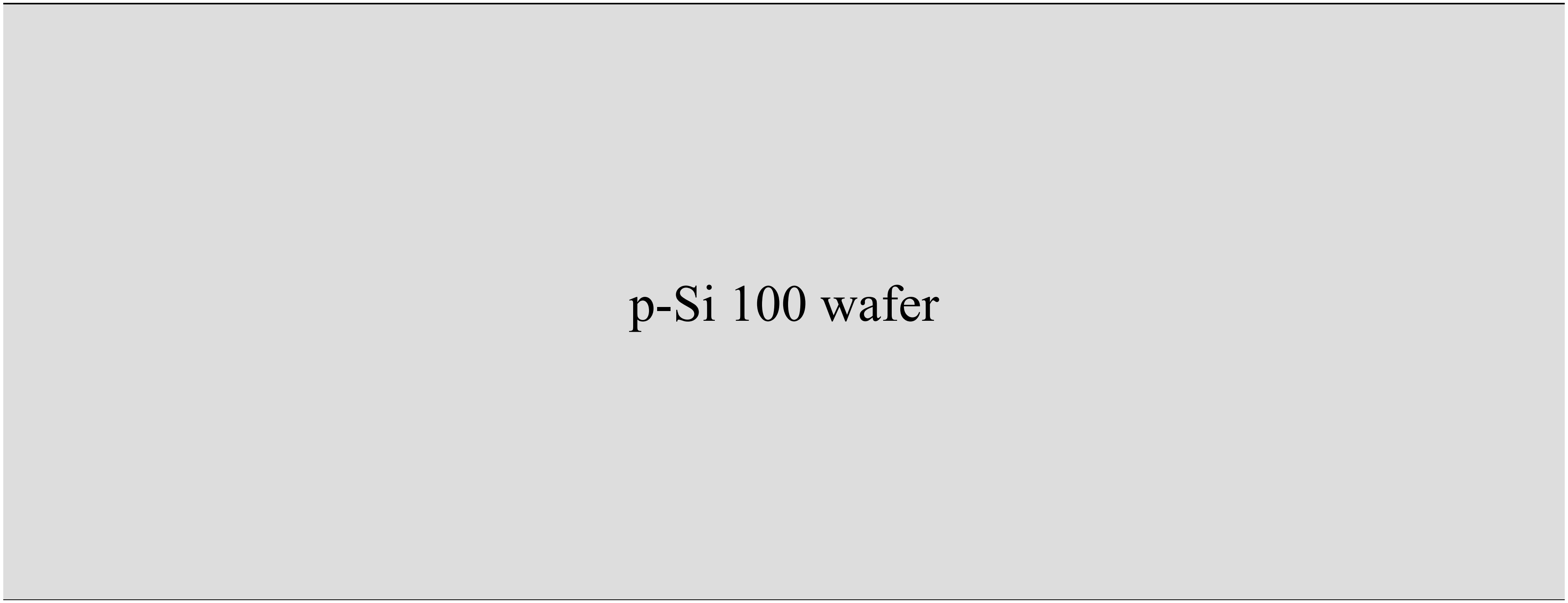
n - channel

functions as a switch
~ 1 billion /chip

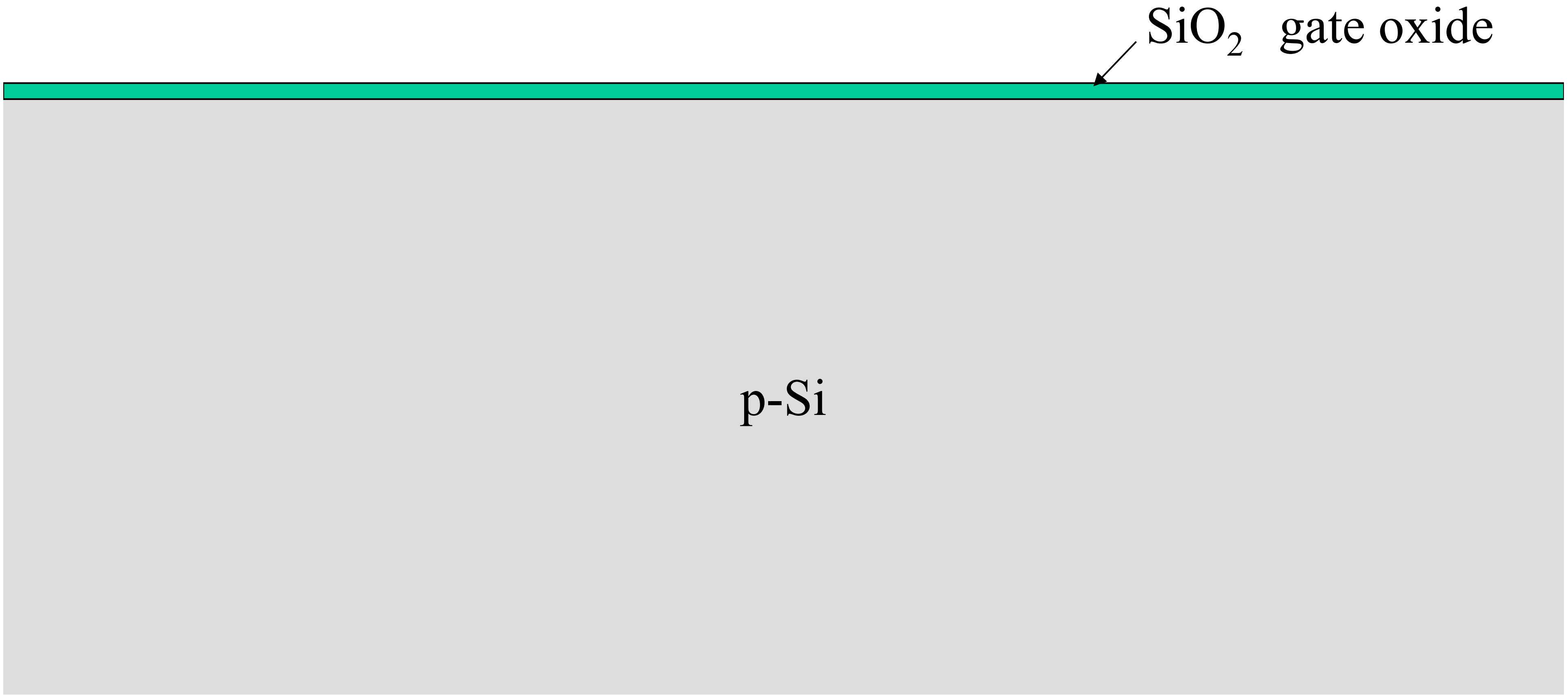


p - channel

Self-aligned fabrication



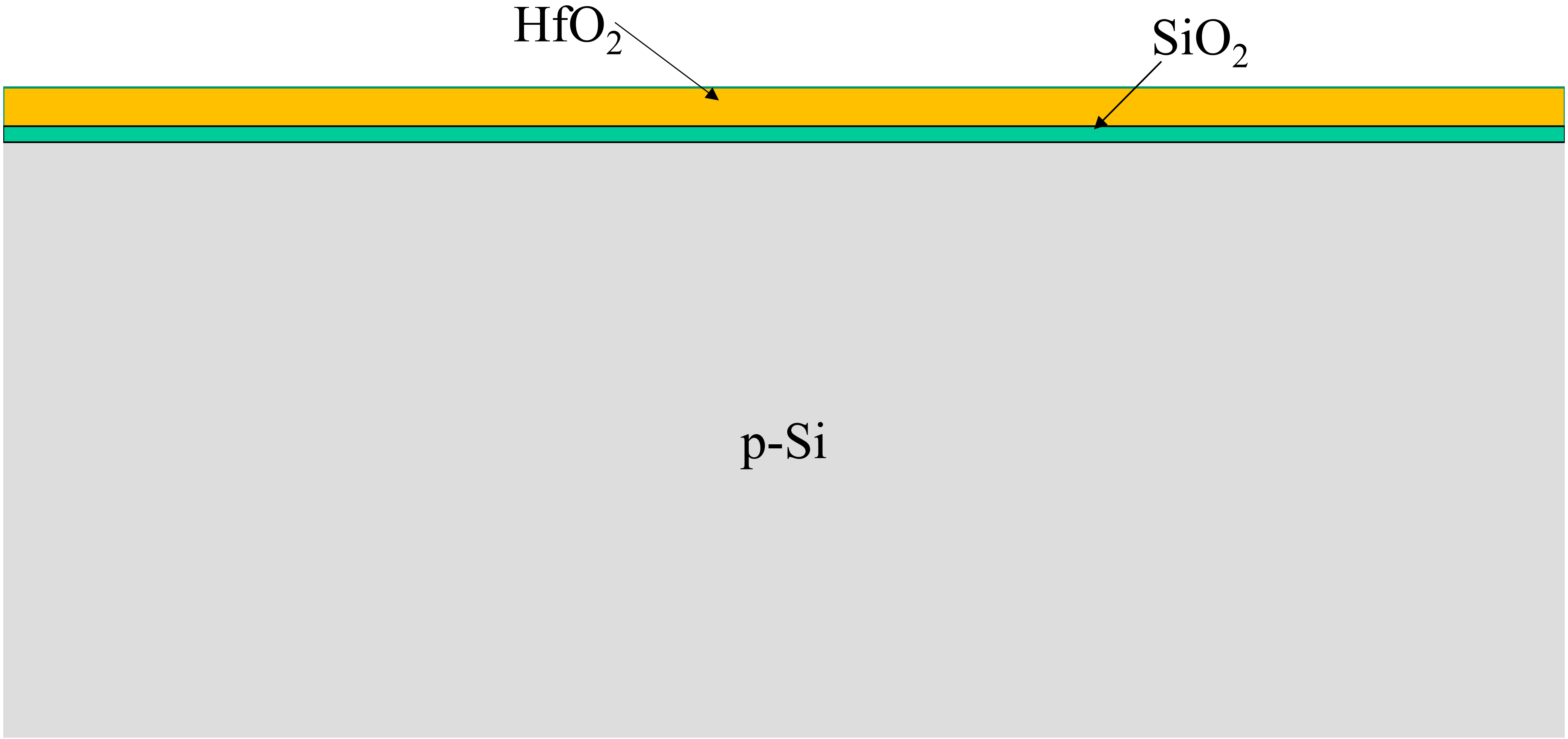
Dry oxidation



SiO_2 gate oxide

p-Si

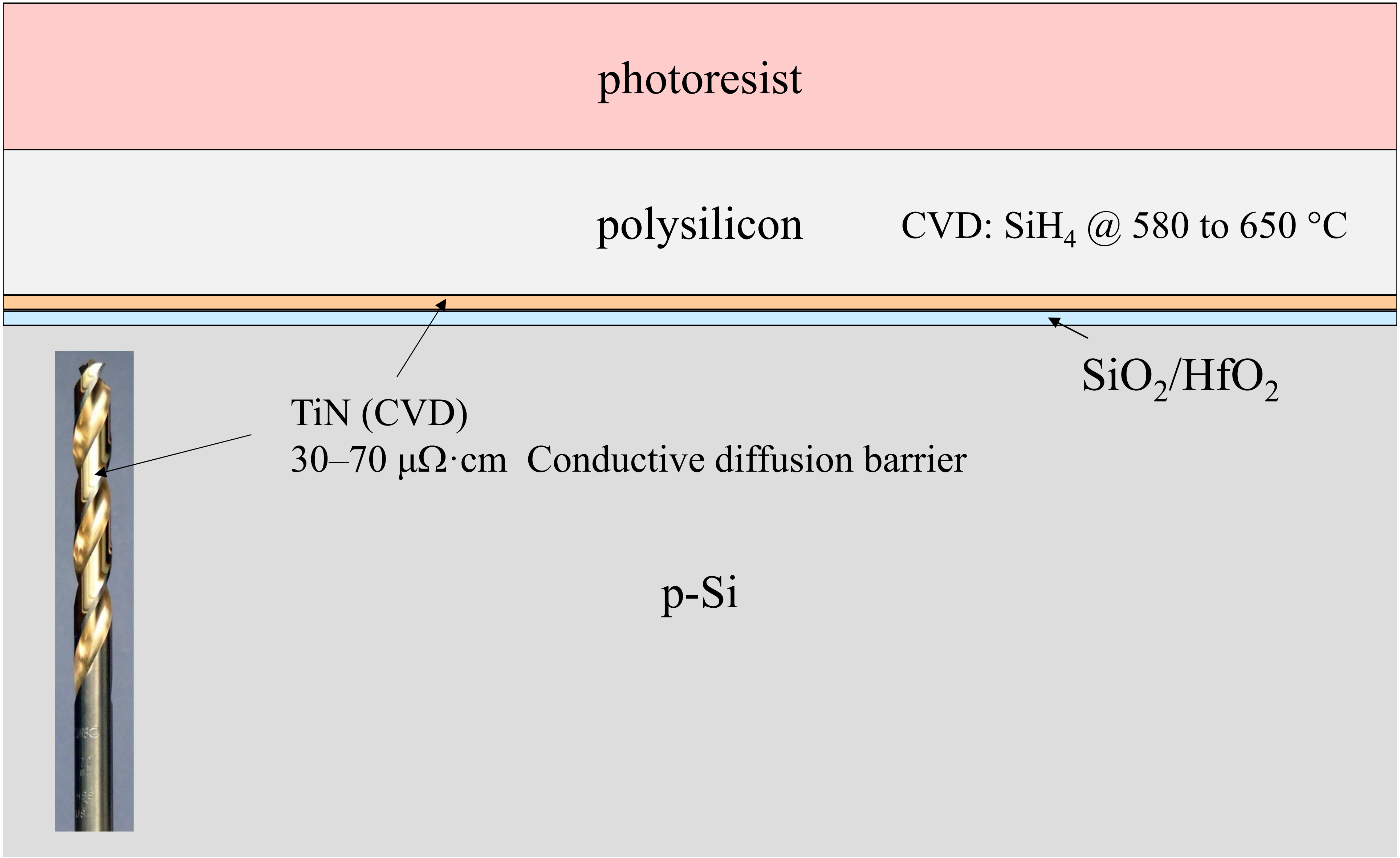
gate oxide



HfO_2

SiO_2

p-Si



photoresist

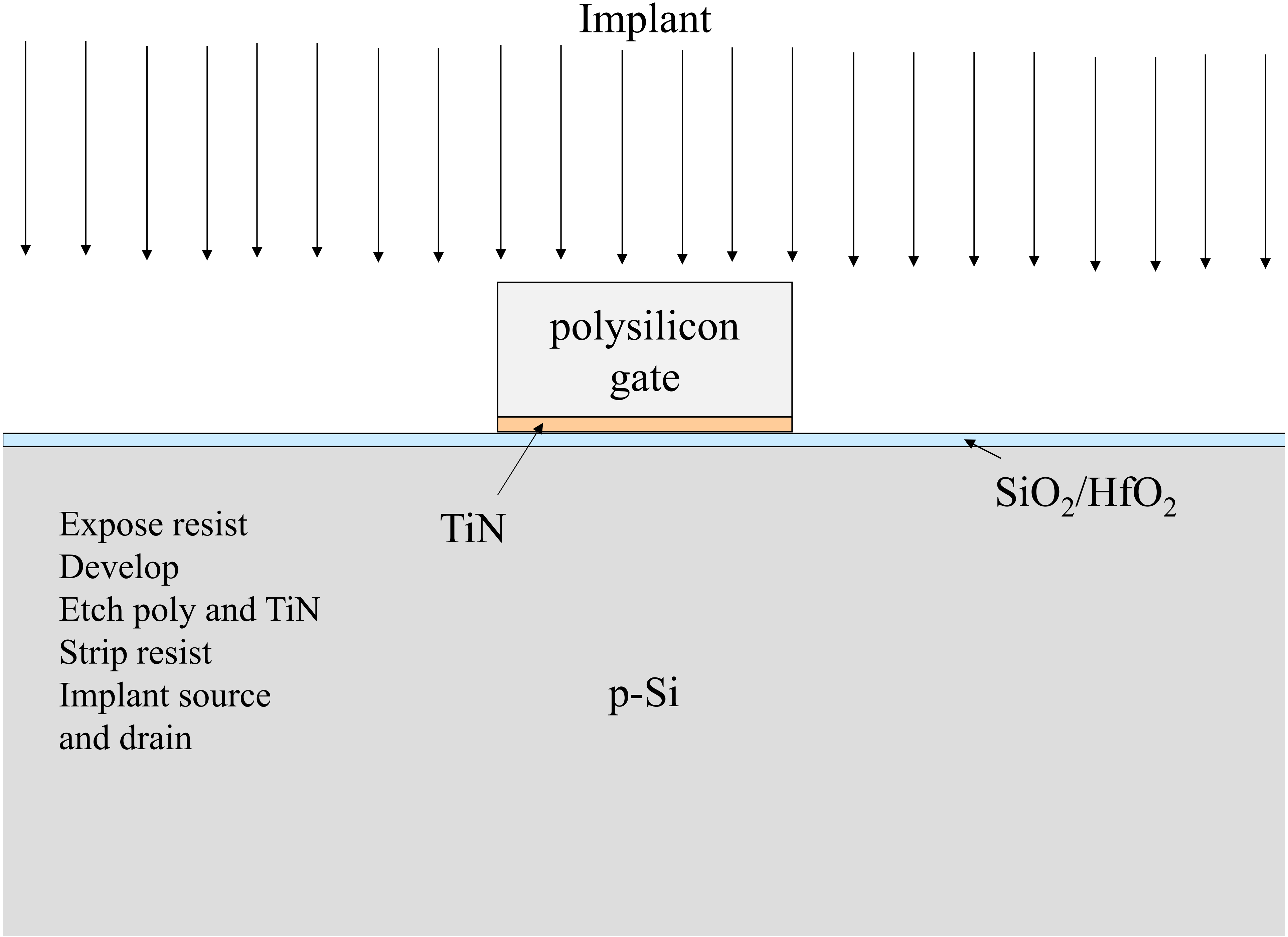
polysilicon

CVD: SiH_4 @ 580 to 650 °C

SiO_2/HfO_2

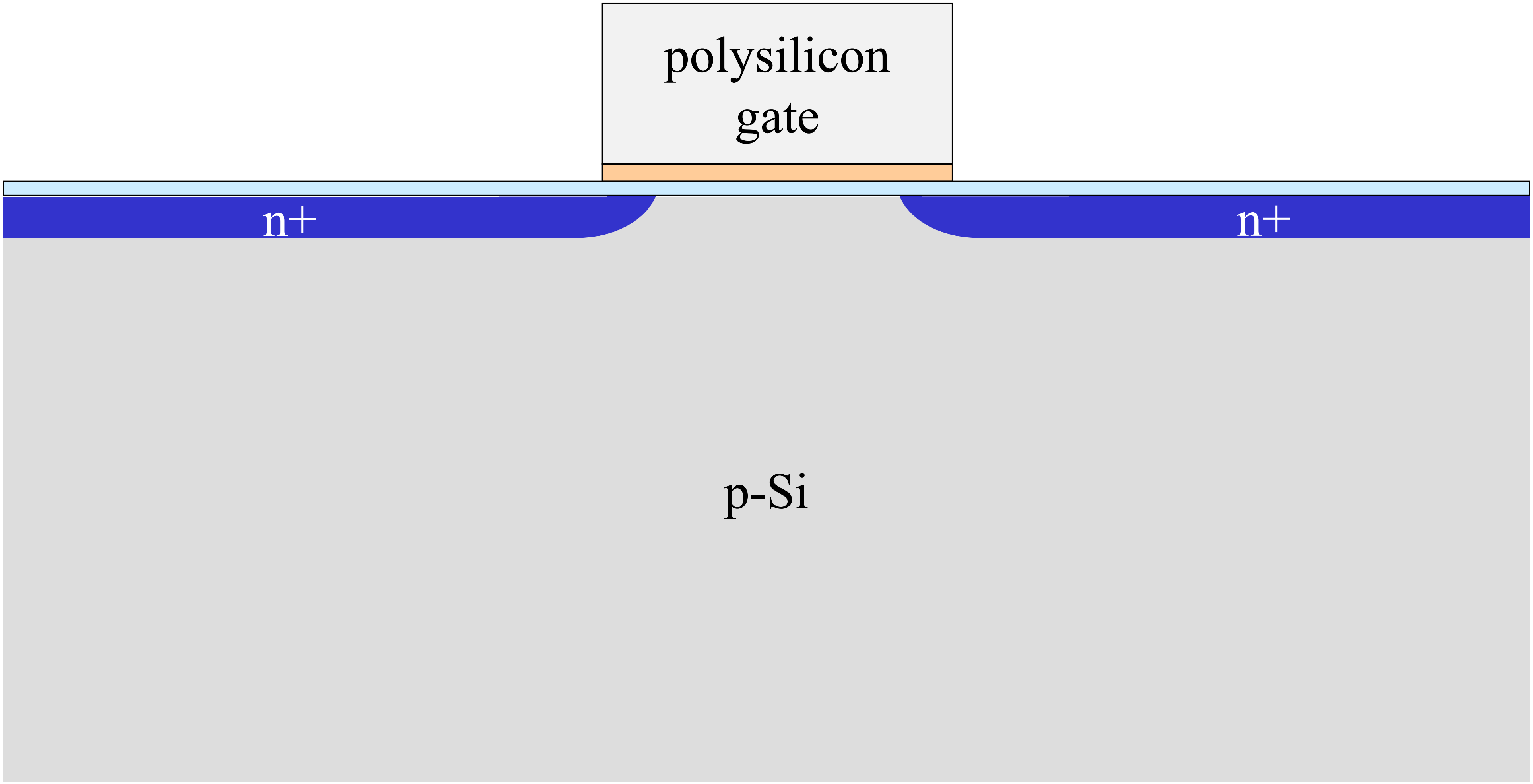
TiN (CVD)
30–70 μΩ·cm Conductive diffusion barrier

p-Si

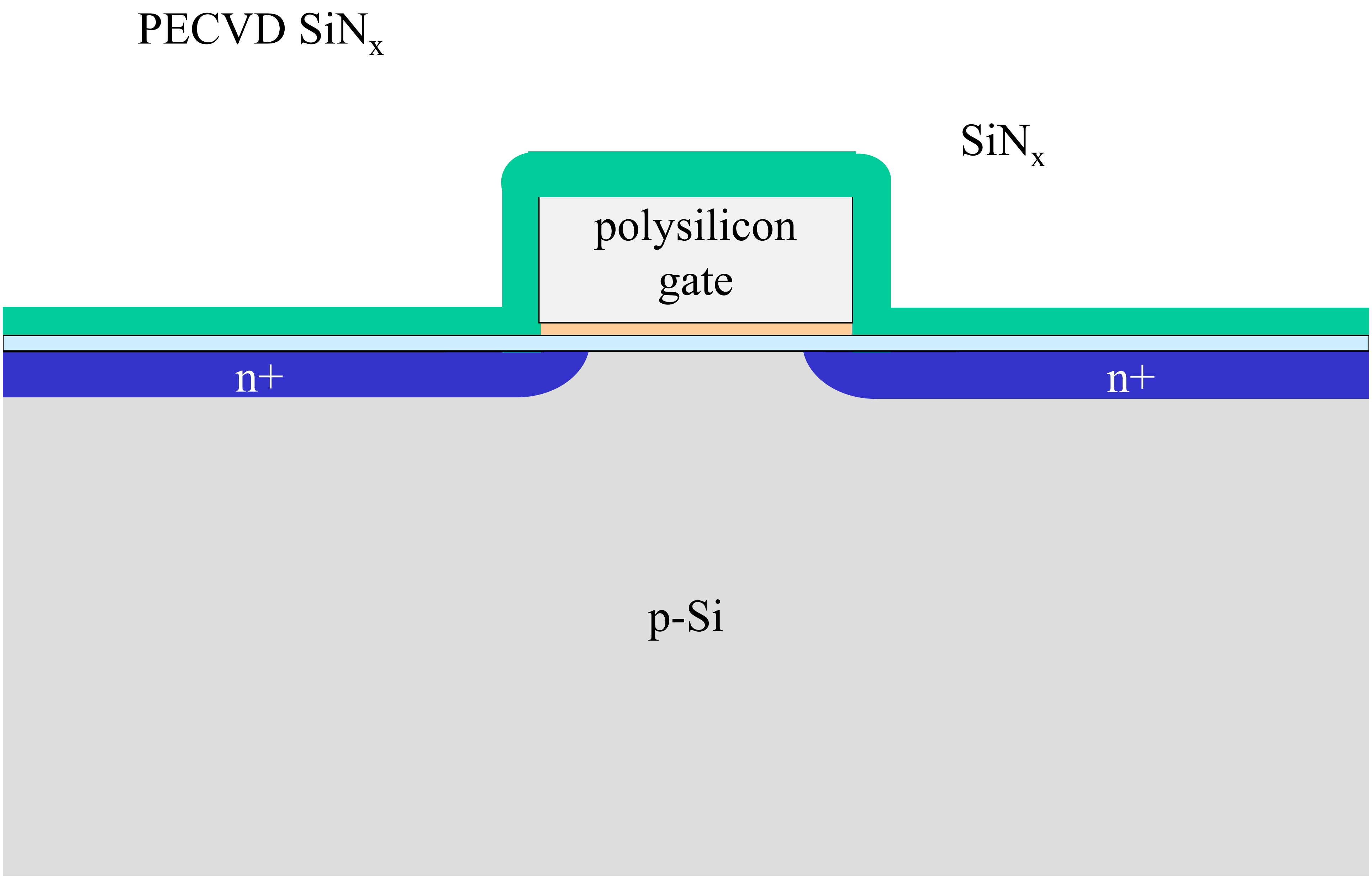


Expose resist
Develop
Etch poly and TiN
Strip resist
Implant source
and drain

Self-aligned fabrication

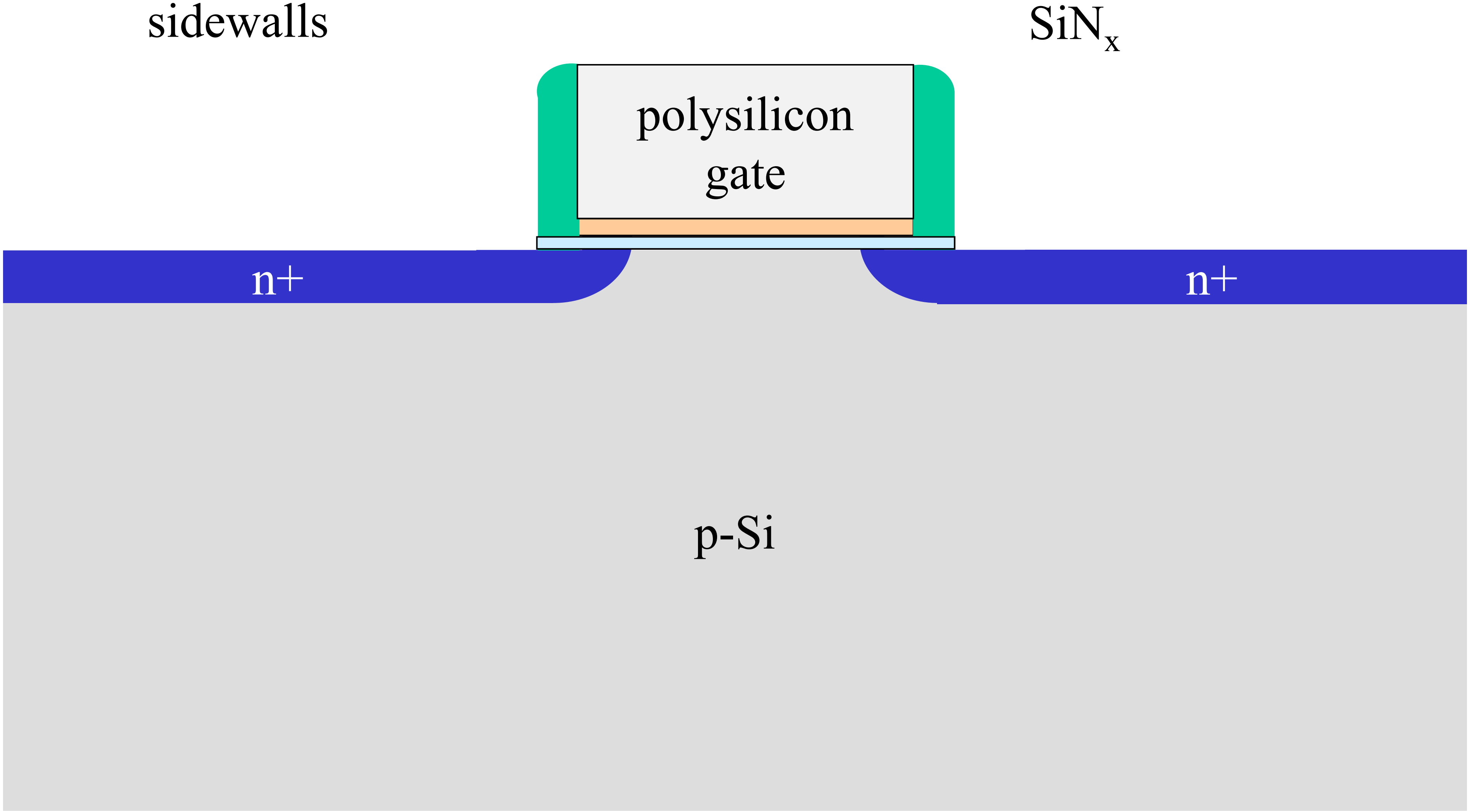


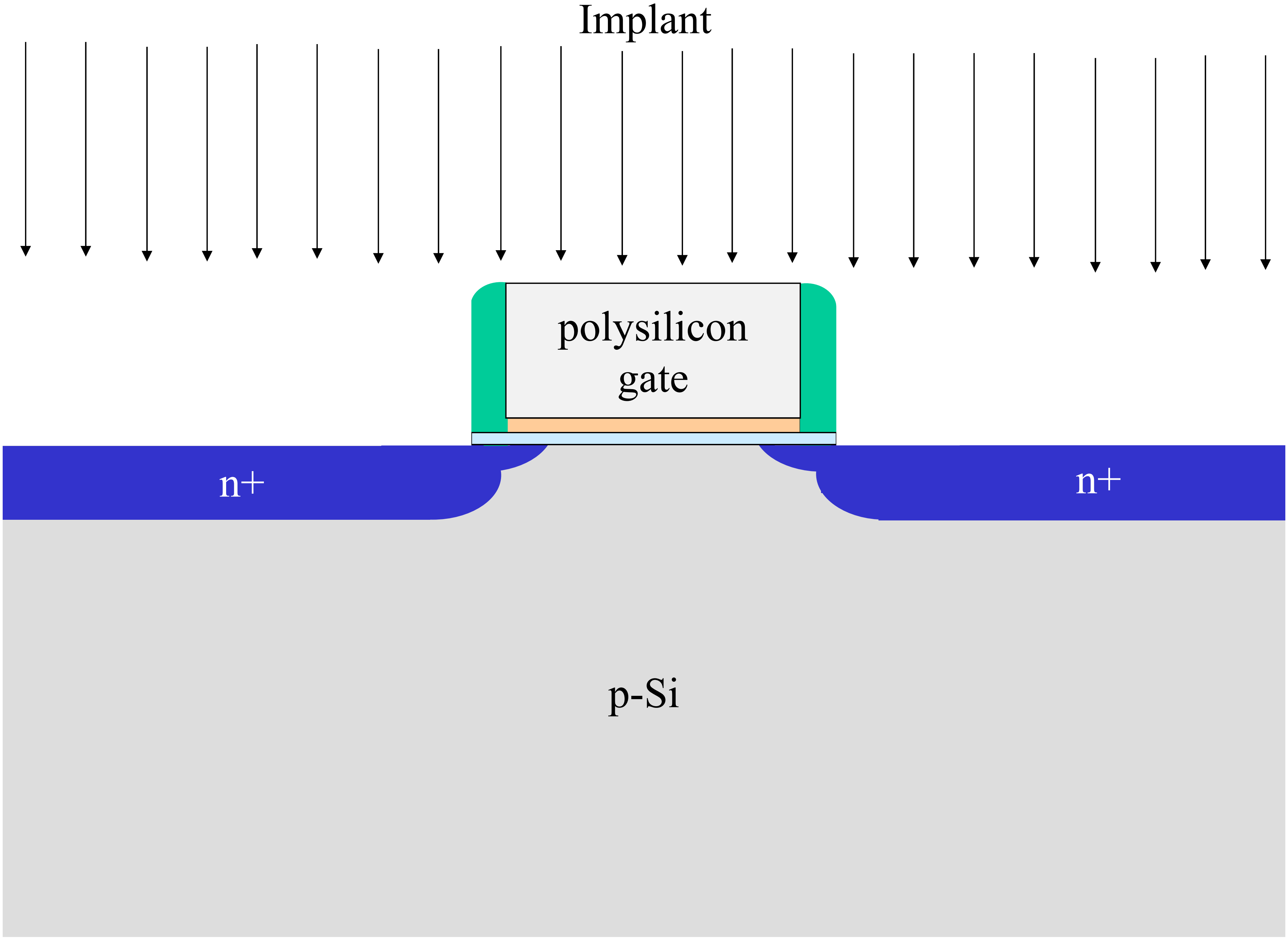
Spacer



Spacer

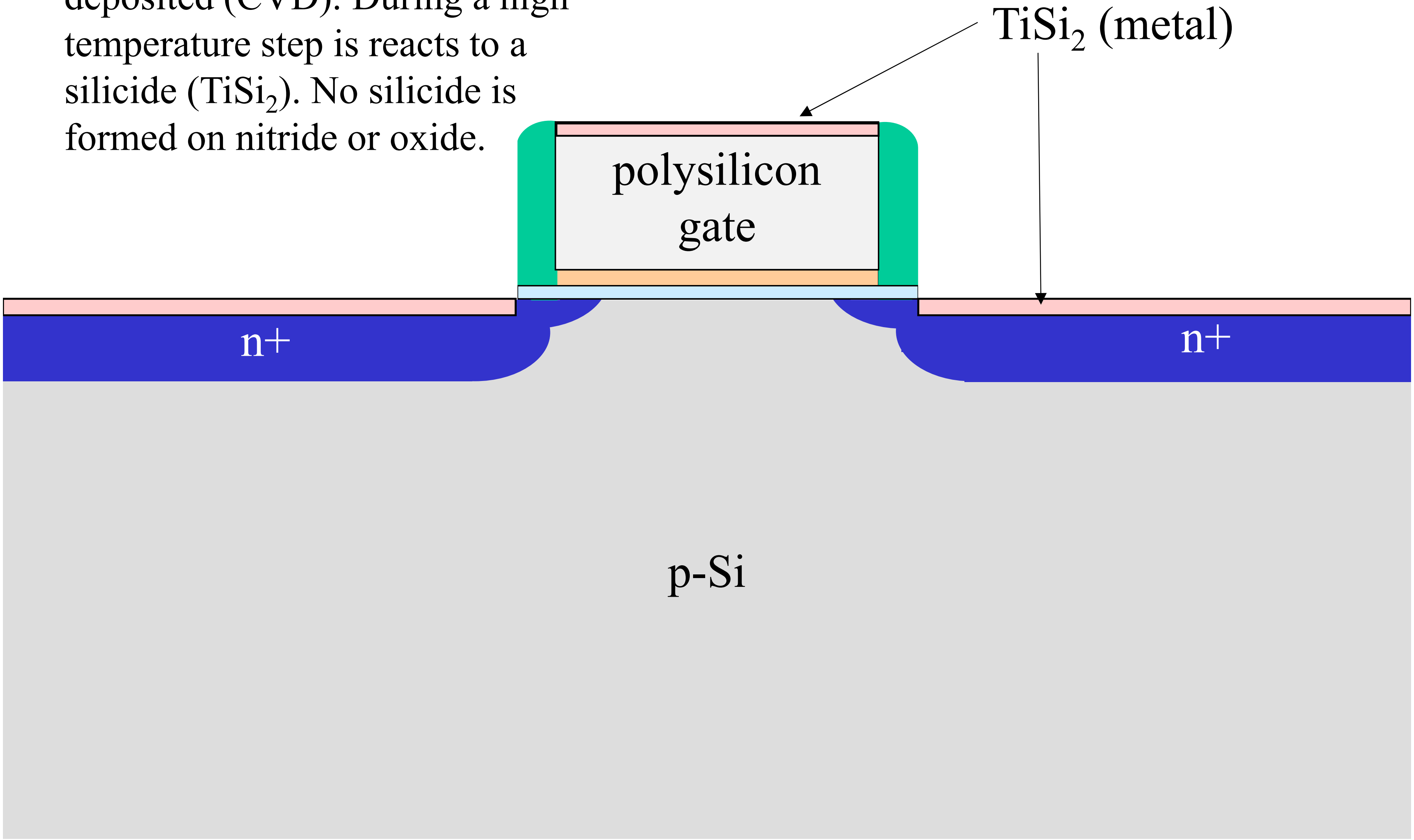
Etch back to
leave only
sidewalls




Implant
polysilicon gate
n+
n+
p-Si

Salicide (Self-aligned silicide)

Transition metal (Ti, Co,W) is deposited (CVD). During a high temperature step is reacts to a silicide ($TiSi_2$). No silicide is formed on nitride or oxide.



CMOS

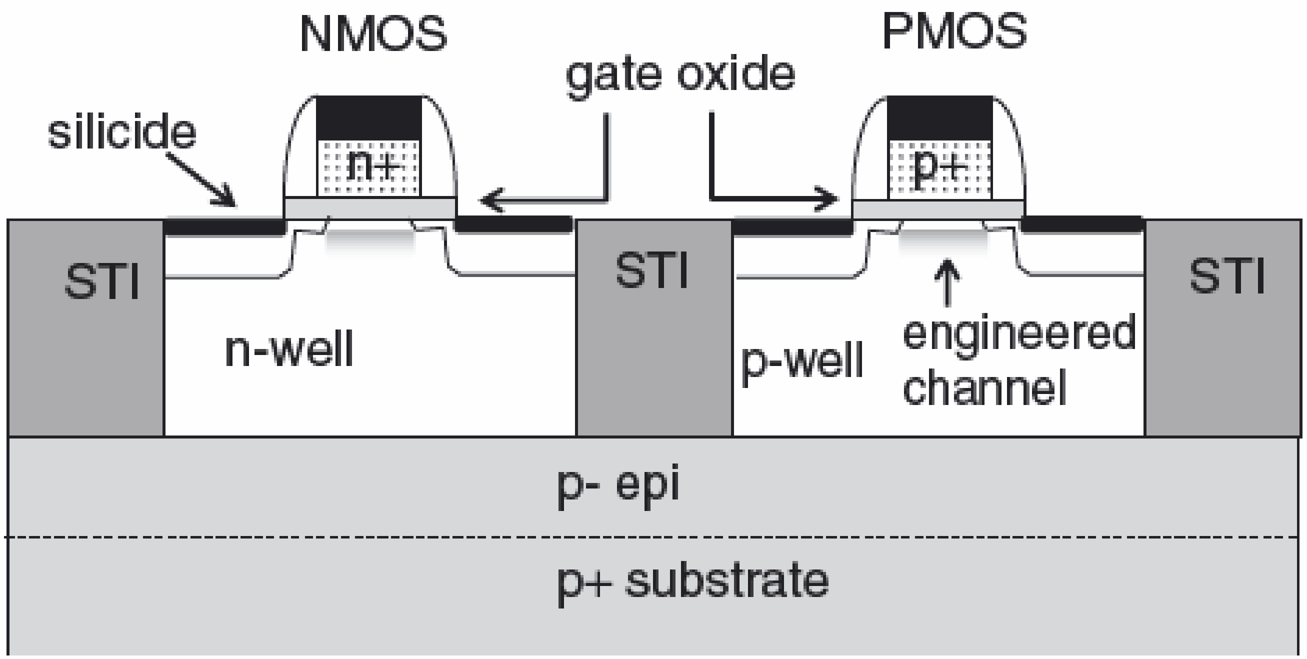
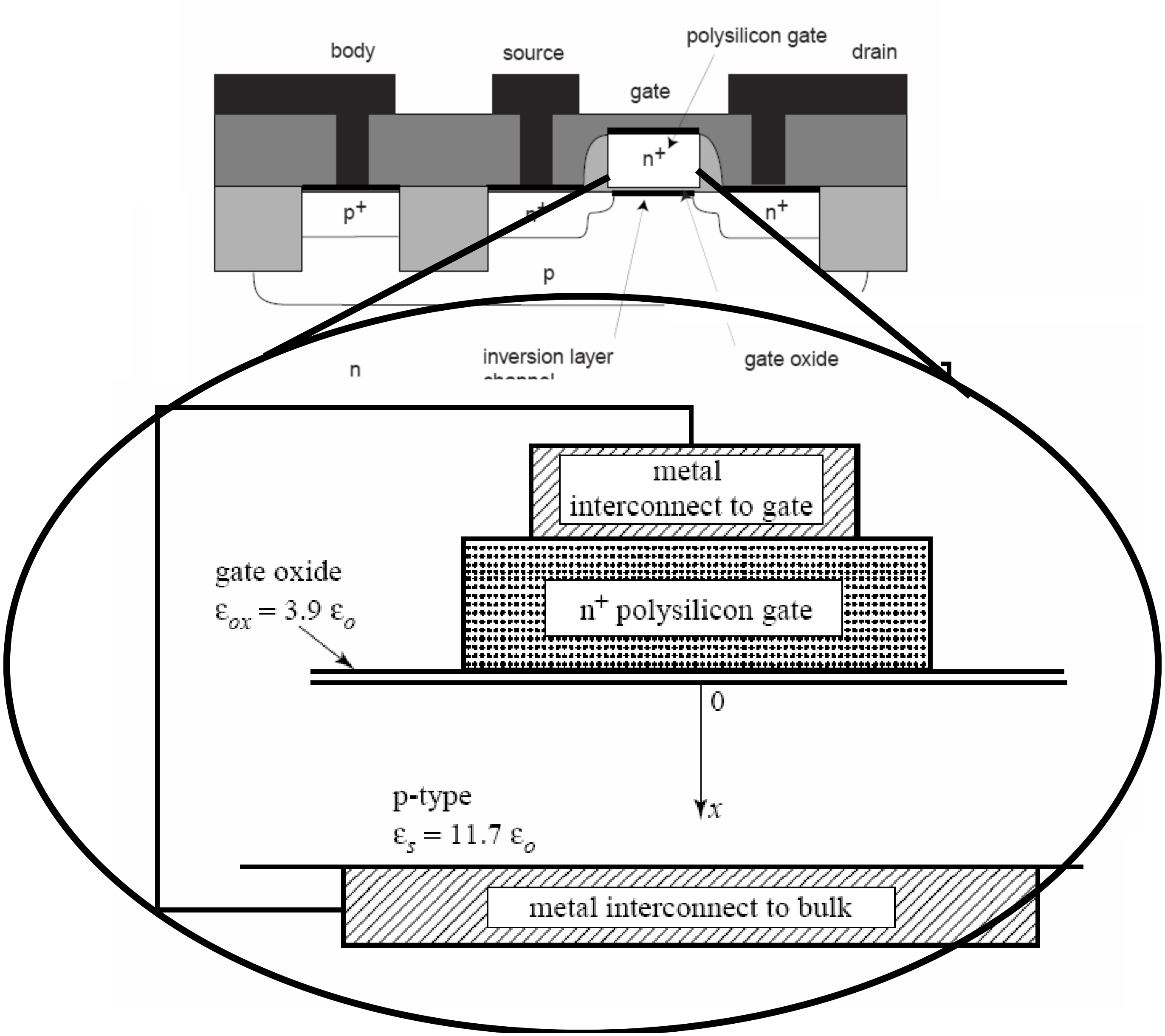


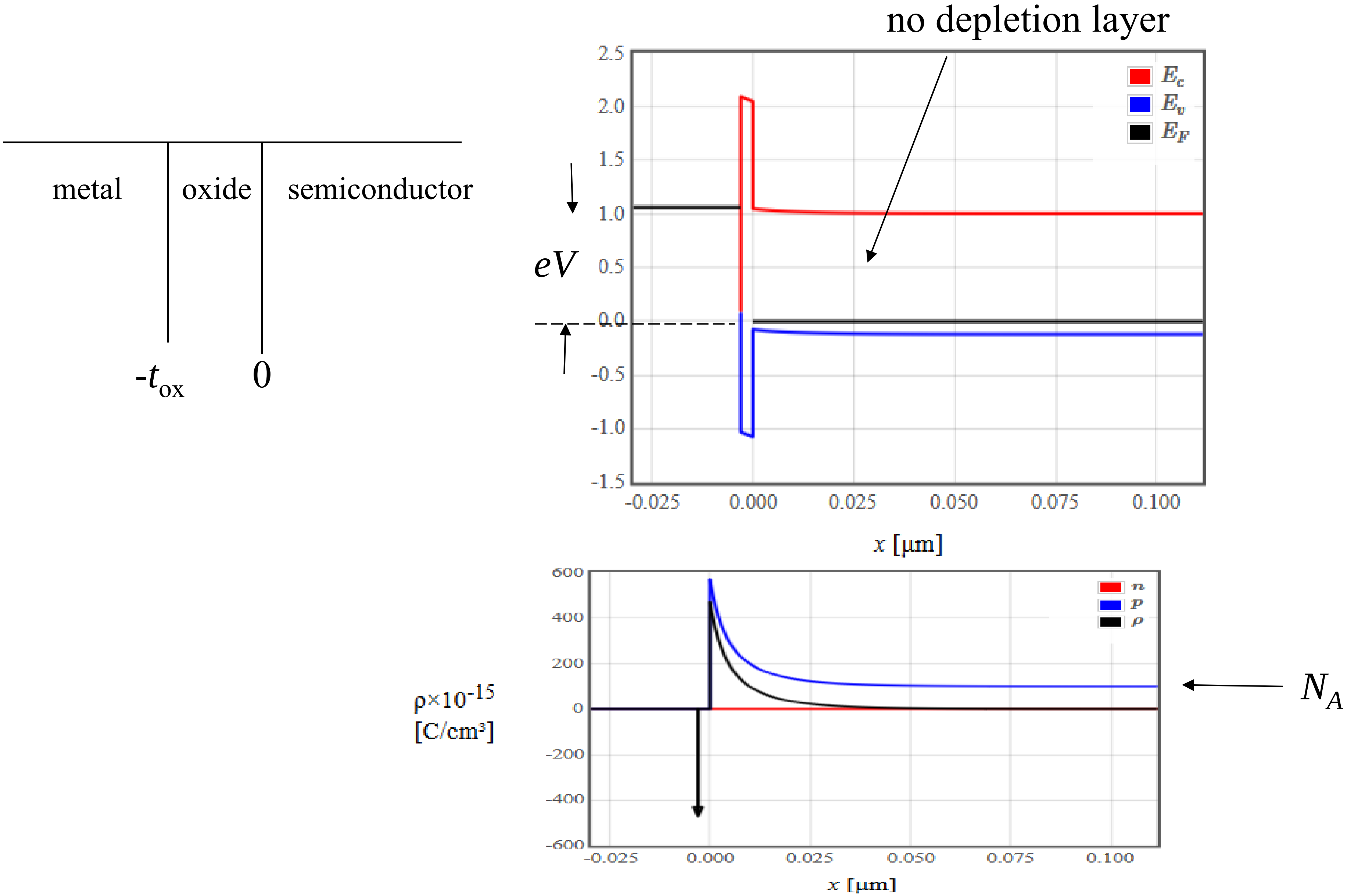
Figure 26.11 Deep submicron CMOS: 200 nm gate length, 5 nm gate oxide, 70 nm junction depth; n^+ poly for NMOS and p^+ poly for PMOS. Shallow trench isolation on epitaxial n^+/p^+ wafer

Source: Fransila

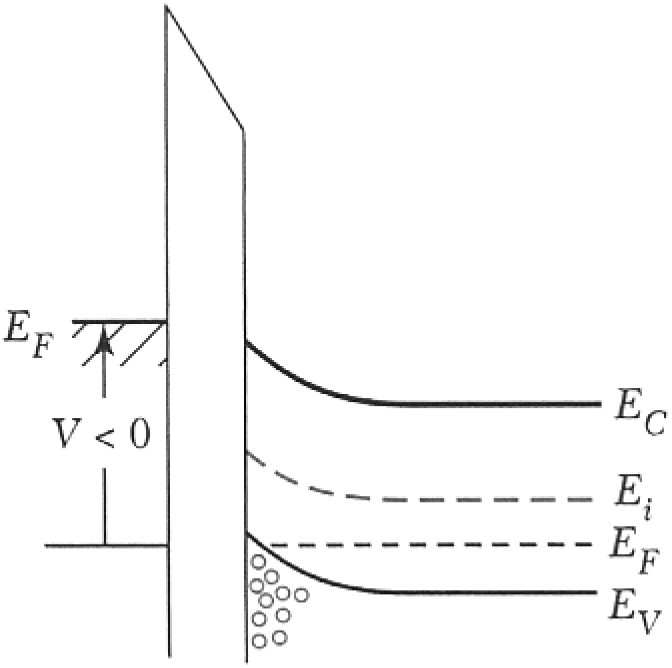
MOS capacitor

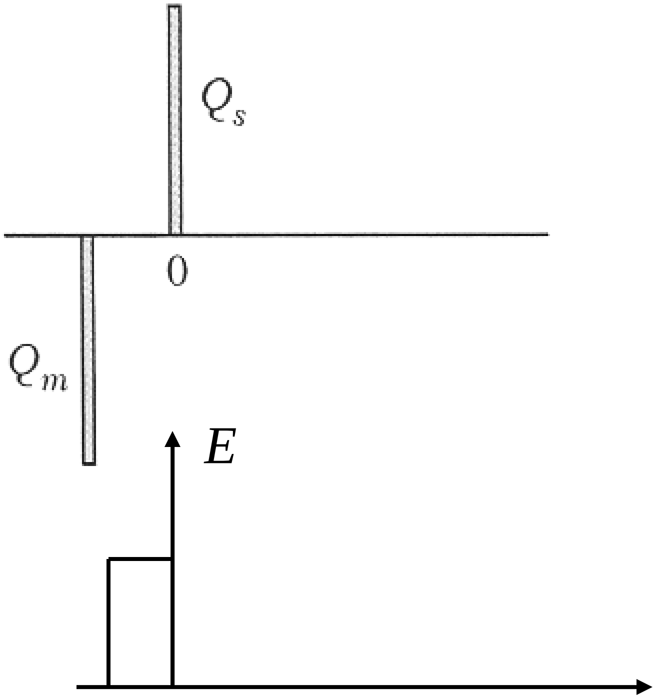


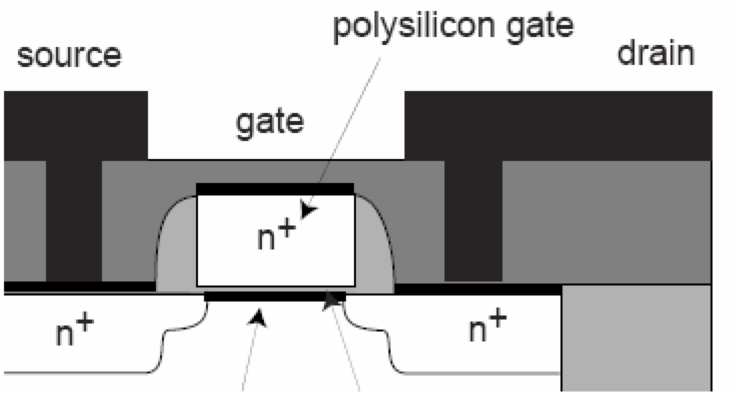
Accumulation



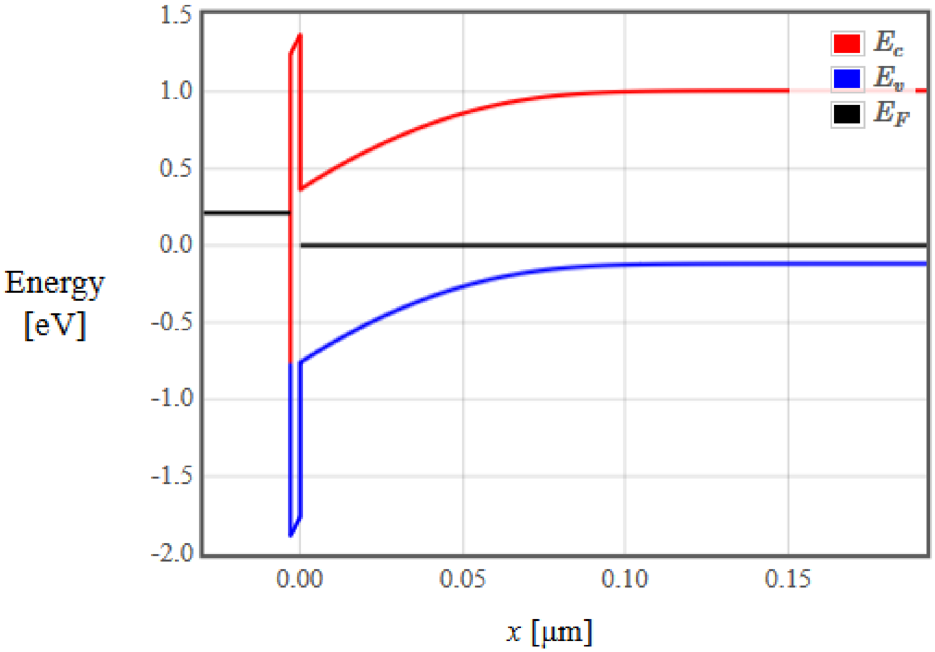
Accumulation



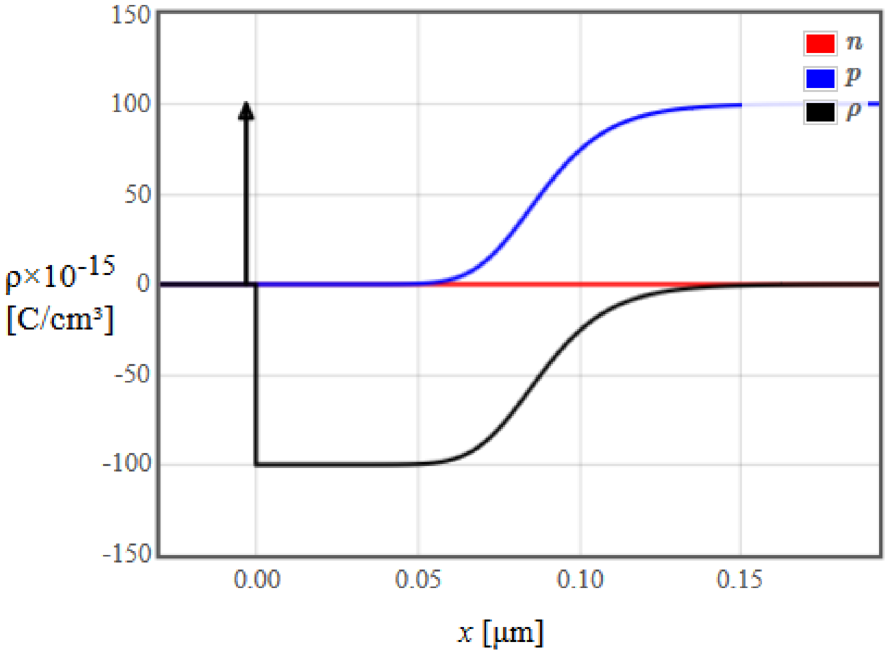




Depletion

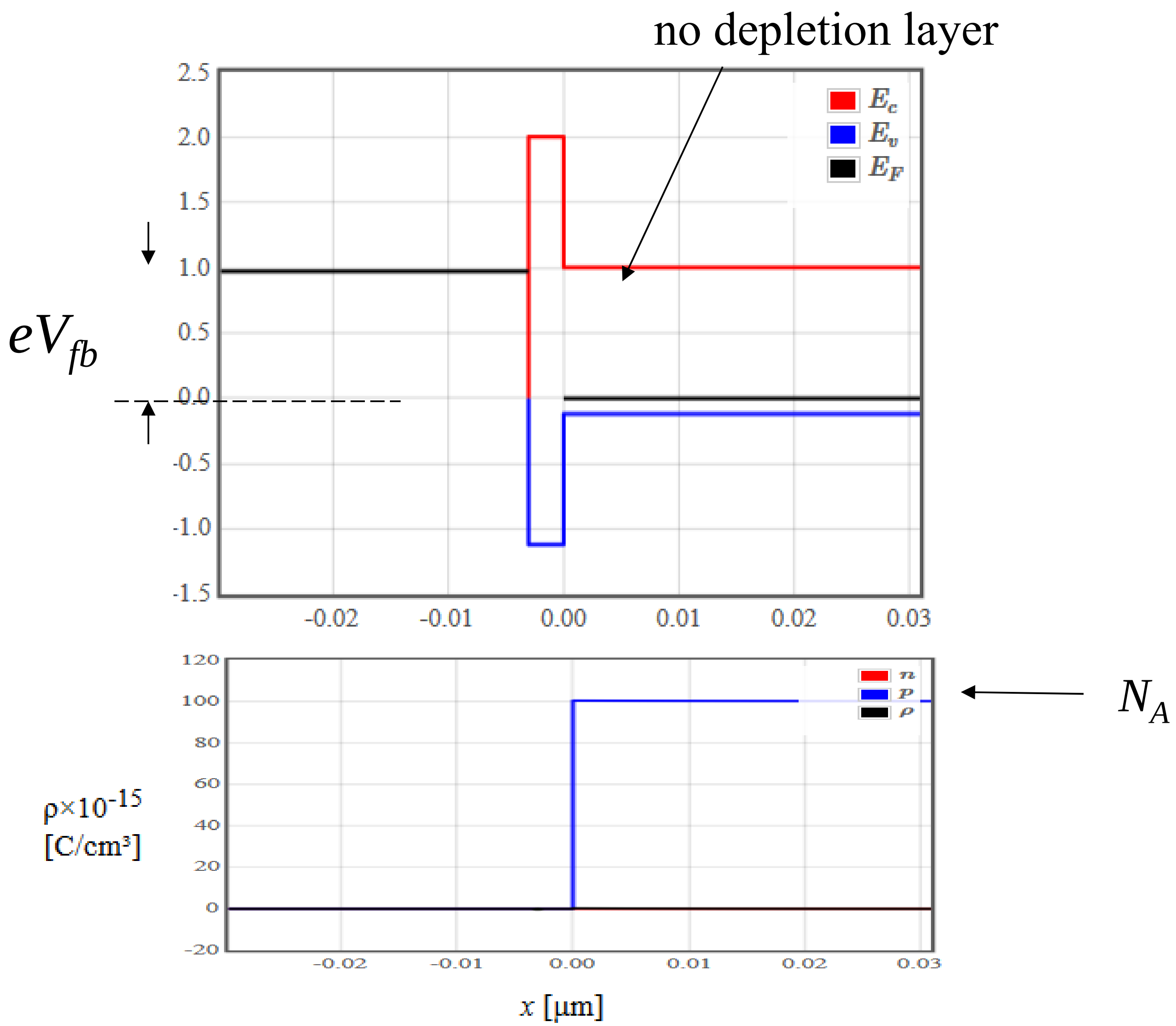


Energy [eV]
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0.00
0.05
0.10
0.15
x [µm]
E_c
E_v
E_F



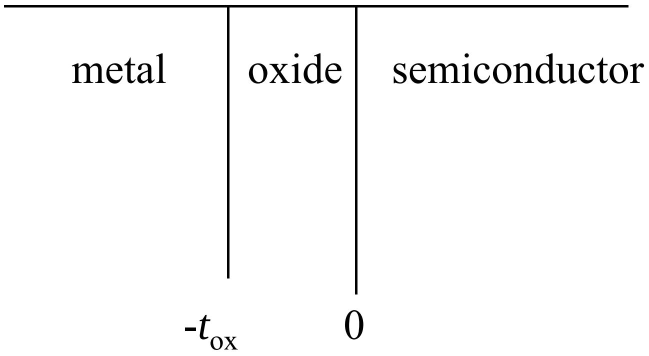
$\rho\times10^{-15}$ [C/cm³]
150
100
50
0
-50
-100
-150
0.00
0.05
0.10
0.15
x [µm]
n
p
ρ

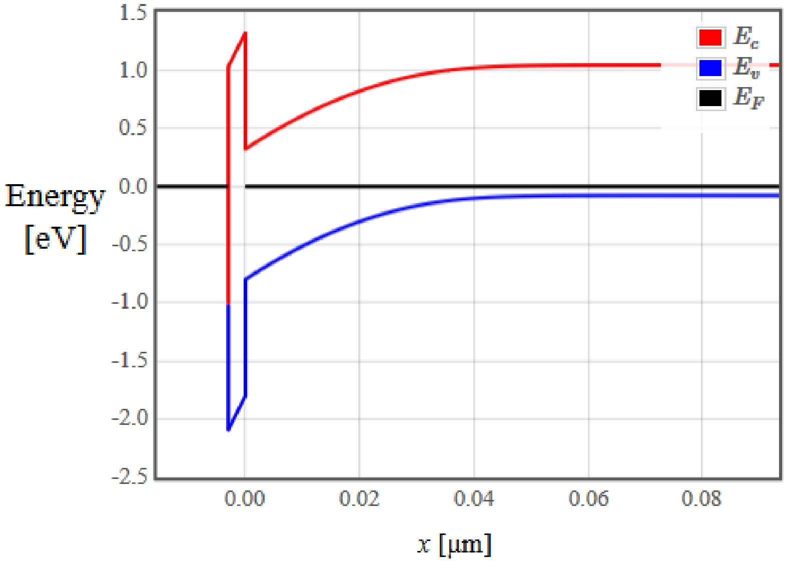
Flat band voltage



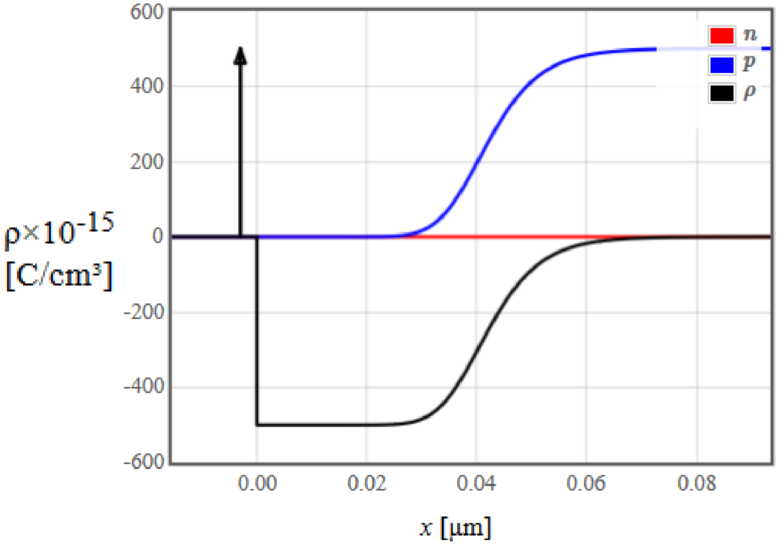
If $\phi_s = \phi_m$, the flatband voltage is the zero bias voltage

Zero bias





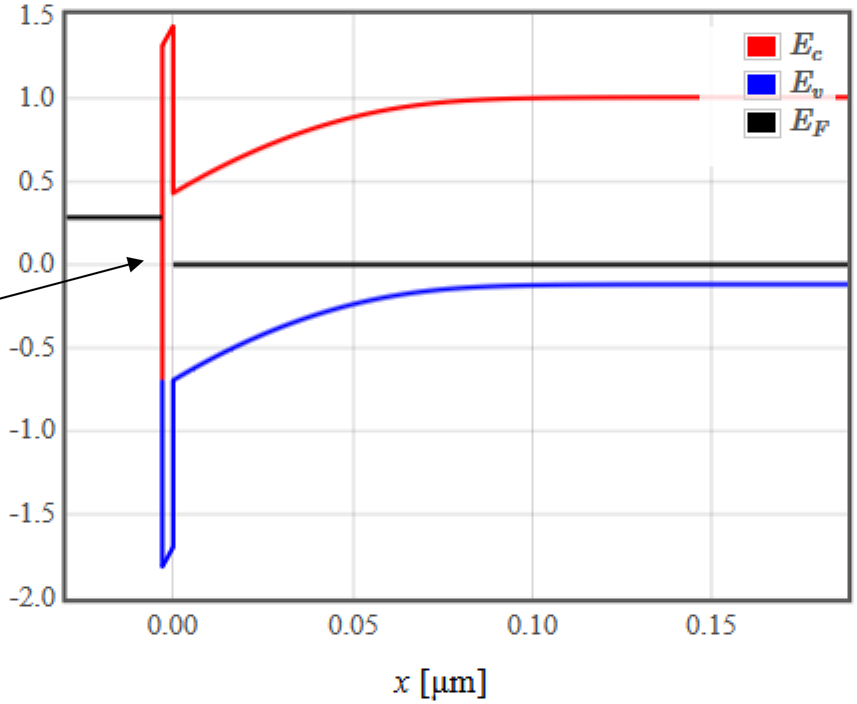
$e\phi_m$
Al 4.1 eV
p+ poly 4.05 eV
n+ poly 5.05 eV



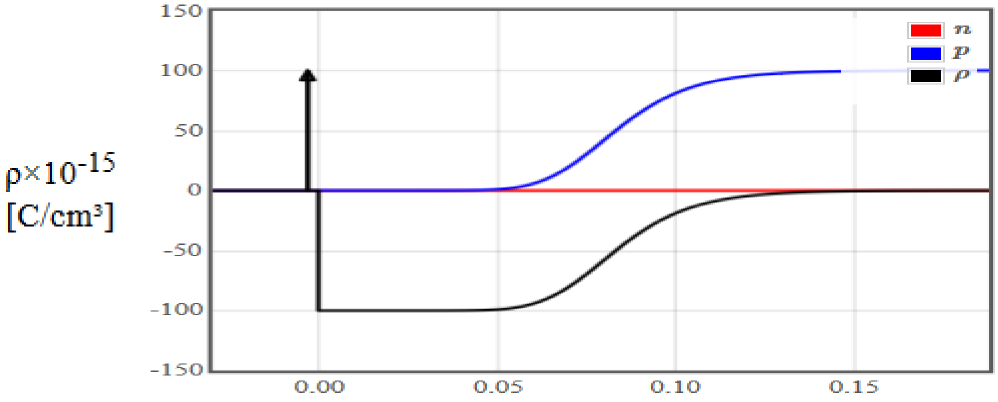
Can be in accumulation or depletion depending on workfunctions

Weak Inversion

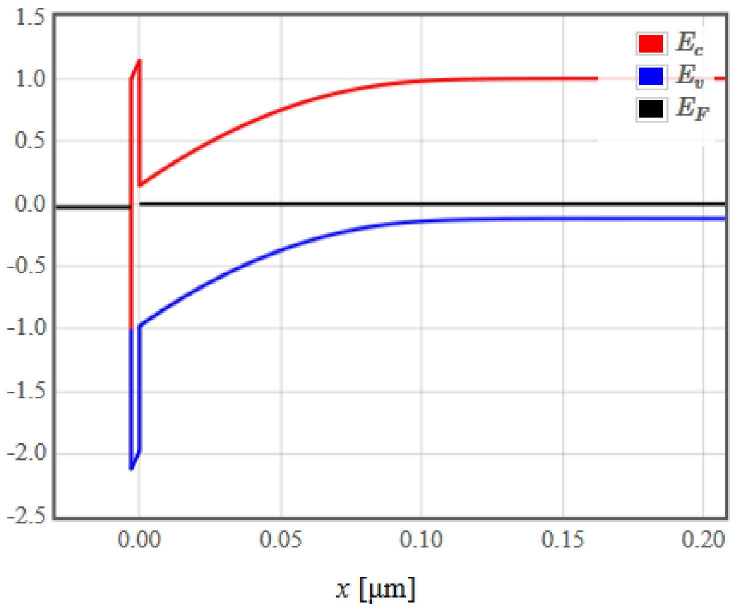
Majority carriers at $x = 0$ change from p to n

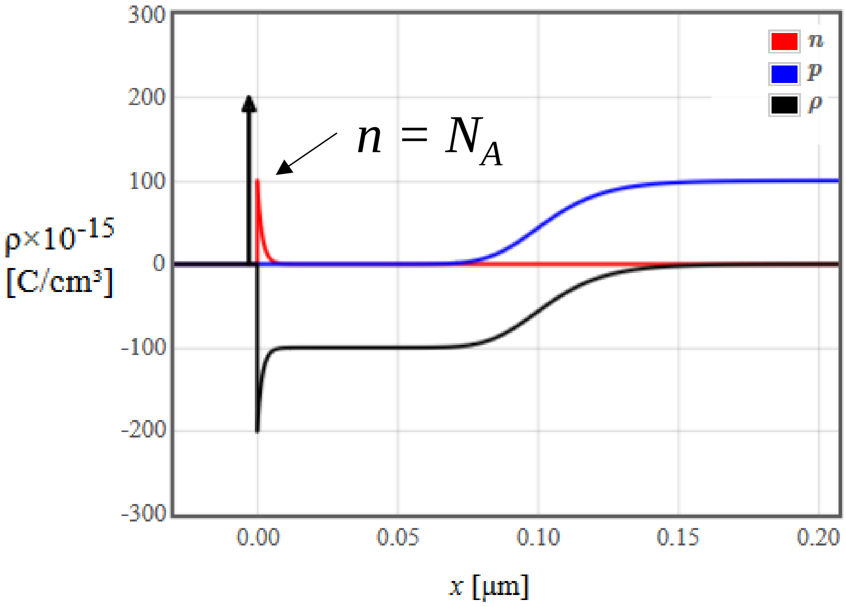


n > p
at the interface



Threshold voltage

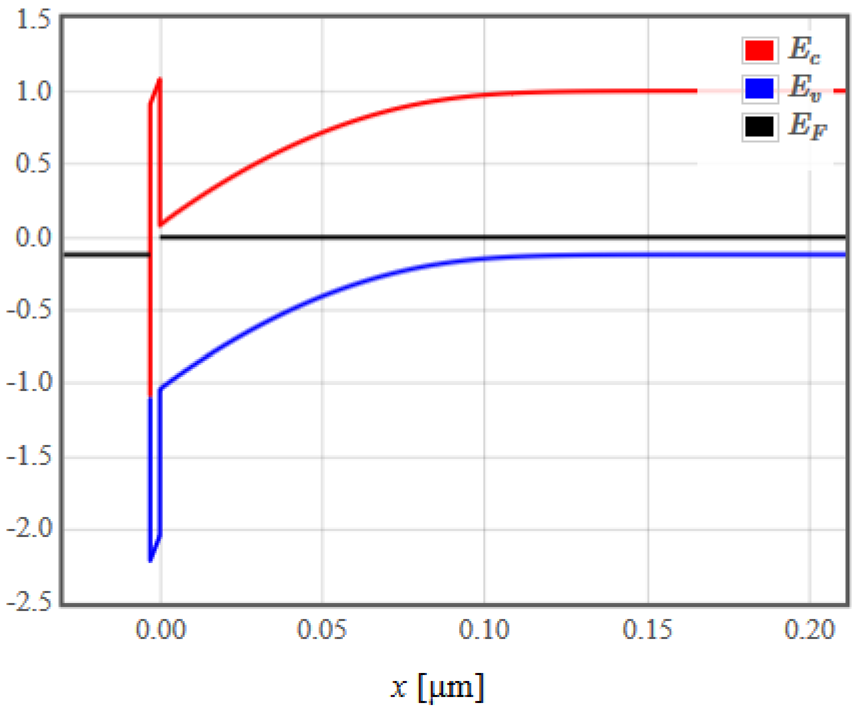


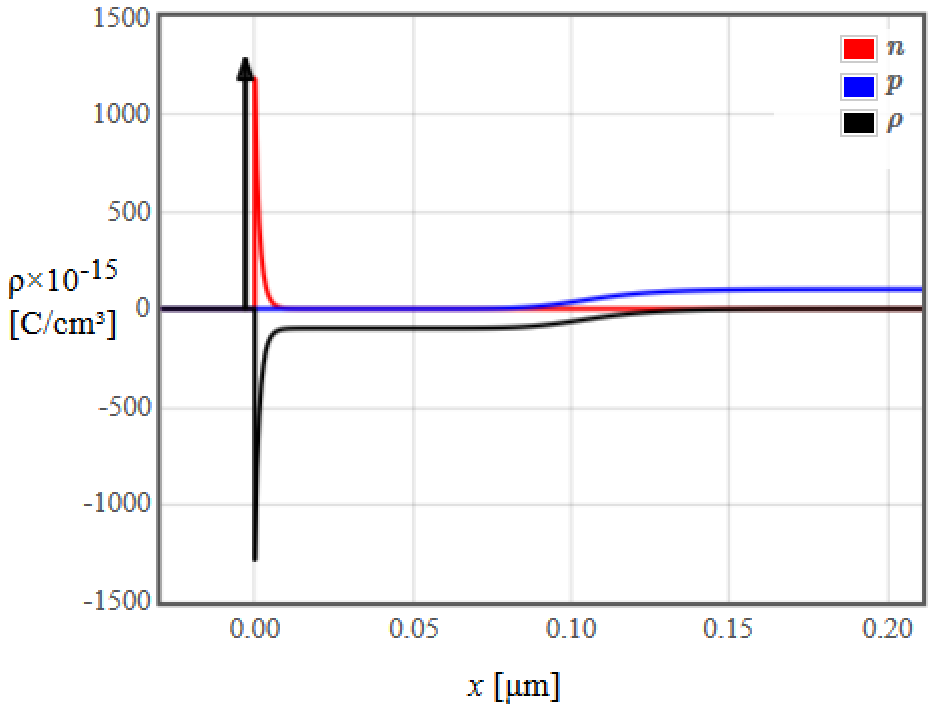


Strong inversion: $n = N_A$ at $x = 0$, the semiconductor-oxide interface

Inversion

$n > N_A$ at $x = 0$, the semiconductor-oxide interface





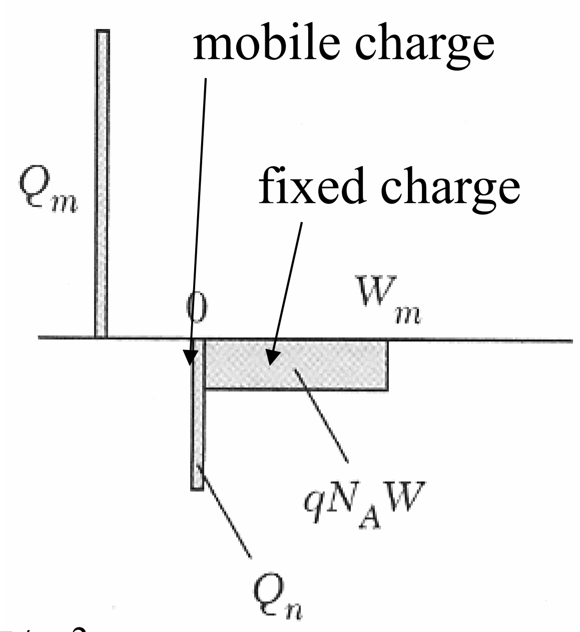
MOS capacitor

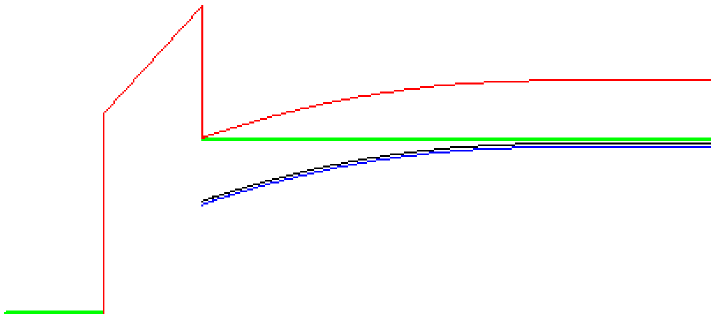
In inversion, the charge in the inversion layer is:

$$Q = -C_{\mathrm{ox}}(V_G - V_B - V_T)$$

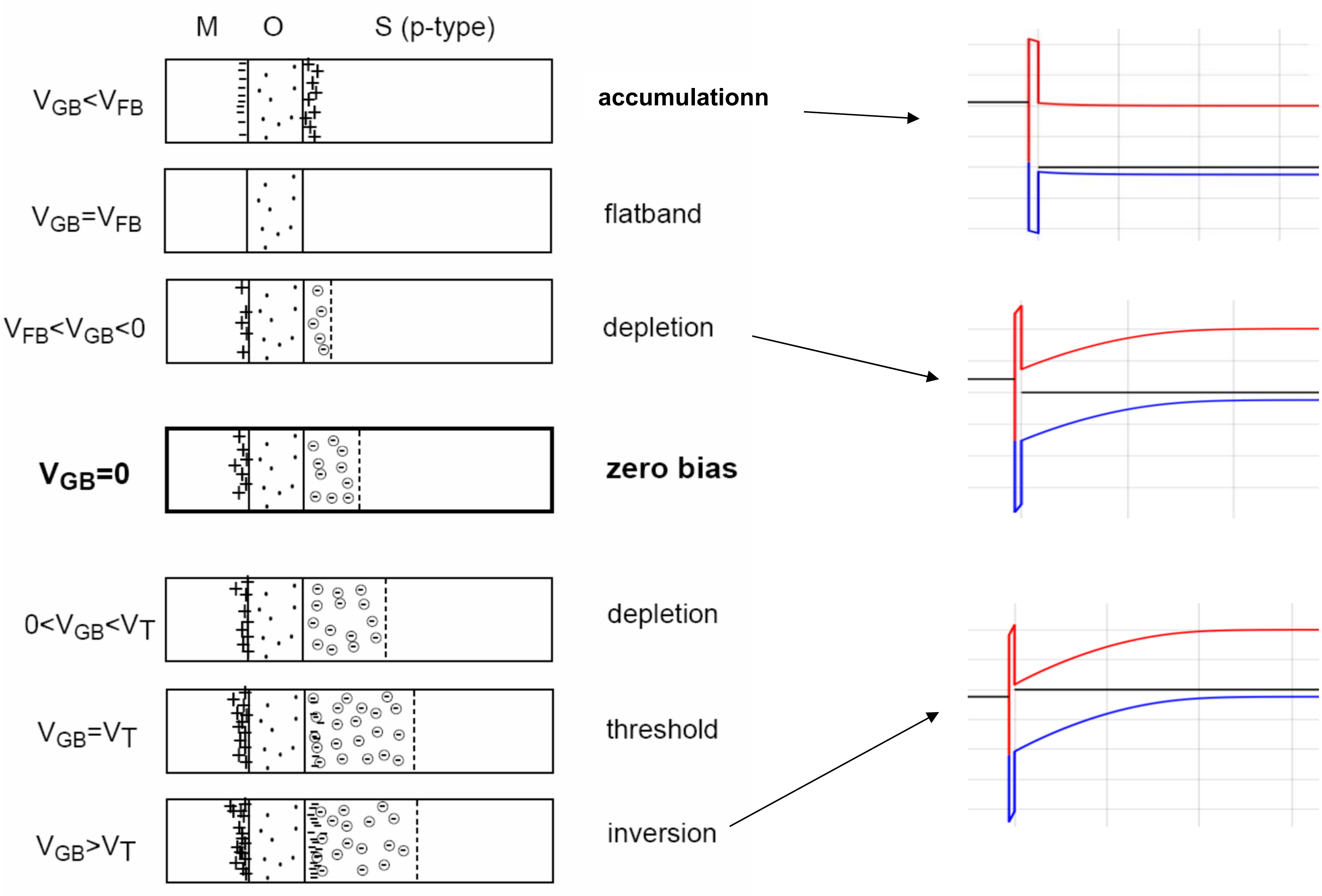
Mobile charge per unit area

Specific capacitance F/m^2





MOS capacitor



accumulationn

flatband

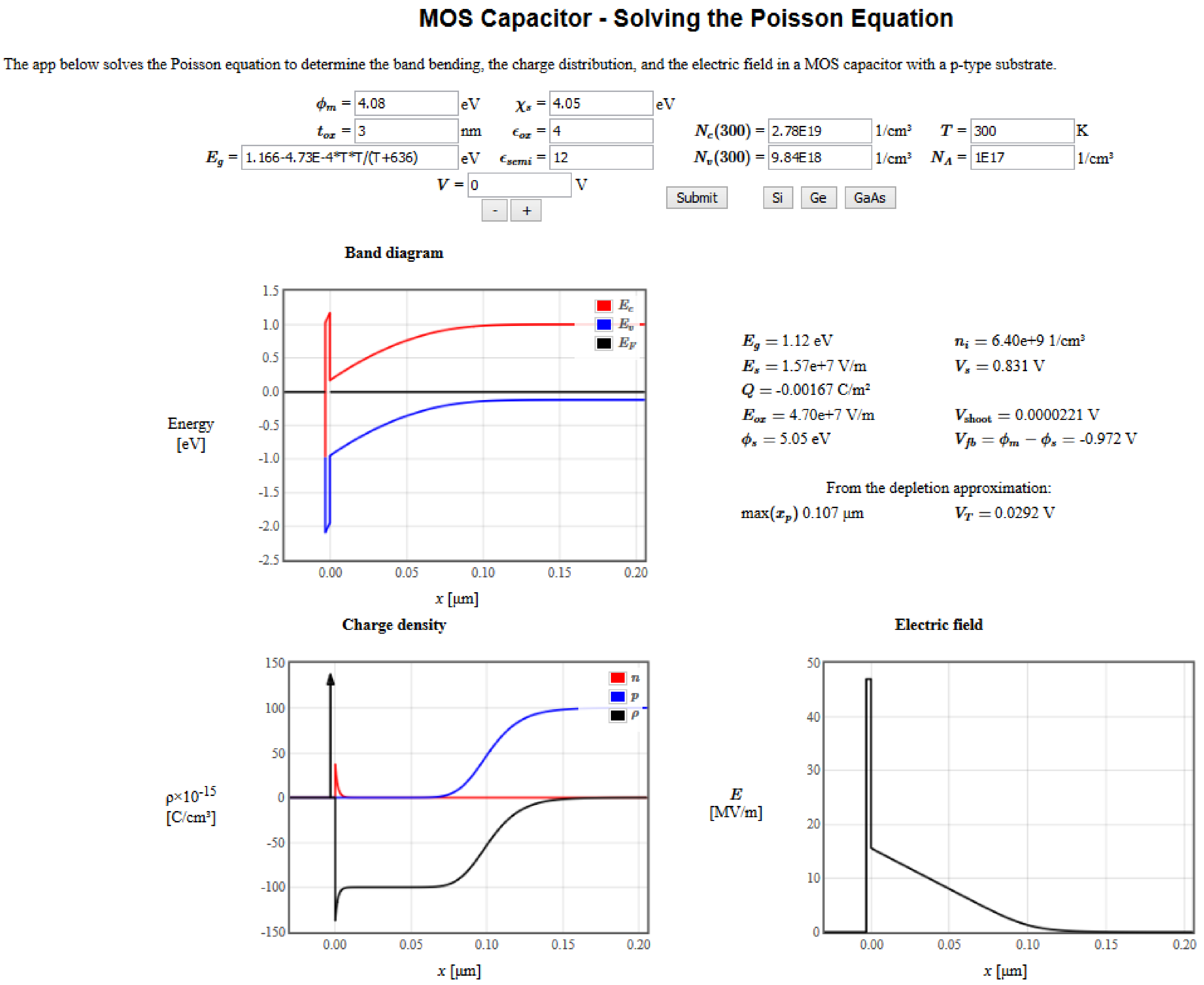
depletion

zero bias

depletion

threshold

inversion



MOS Capacitor - Solving the Poisson Equation

The app below solves the Poisson equation to determine the band bending, the charge distribution, and the electric field in a MOS capacitor with a p-type substrate.

ϕ_m = 4.08 eV

χ_s = 4.05 eV

t_{ox} = 3 nm

ϵ_{ox} = 4

$N_c(300)$ = 2.78E19 1/cm³

T = 300 K

E_g = 1.166-4.73E-4*T*T/(T+636) eV

ϵ_{semi} = 12

$N_v(300)$ = 9.84E18 1/cm³

N_A = 1E17 1/cm³

V = 0 V

Band diagram

E_g = 1.12 eV

n_i = 6.40e+9 1/cm³

E_s = 1.57e+7 V/m

V_s = 0.831 V

Q = -0.00167 C/m²

E_{ox} = 4.70e+7 V/m

V_{shoot} = 0.0000221 V

ϕ_s = 5.05 eV

$V_{fb} = \phi_m - \phi_s$ = -0.972 V

From the depletion approximation:

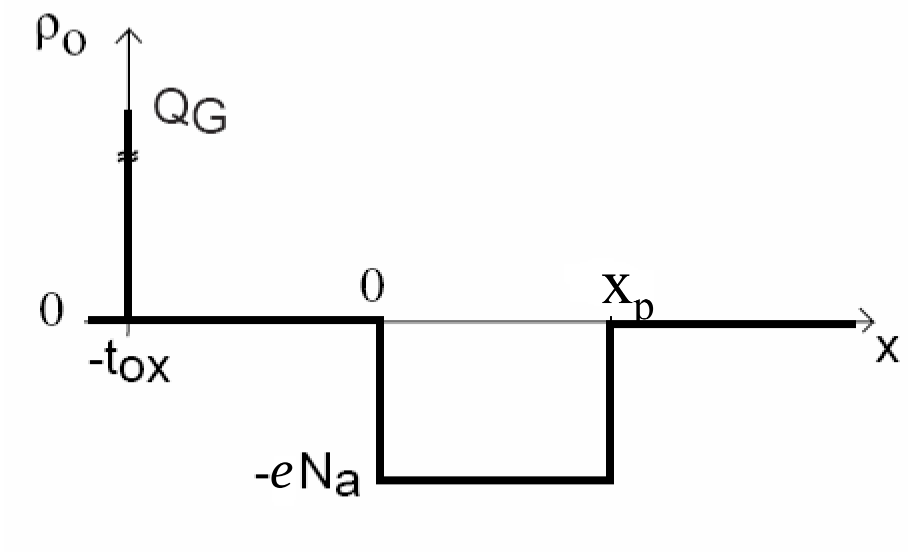
max(x_p) 0.107 µm

V_T = 0.0292 V

Charge density

Electric field

charge density (depletion)

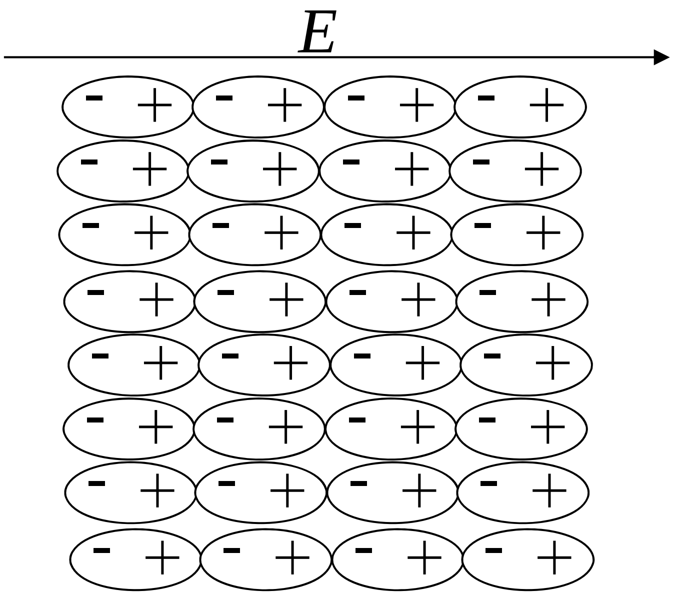


$$-t_{ox} < x < 0 \qquad \rho(x) = 0$$

$$0 < x < x_p \qquad \rho(x) = -eN_A$$

$$x_p < x \qquad \rho(x) = 0$$

electric field (depletion)

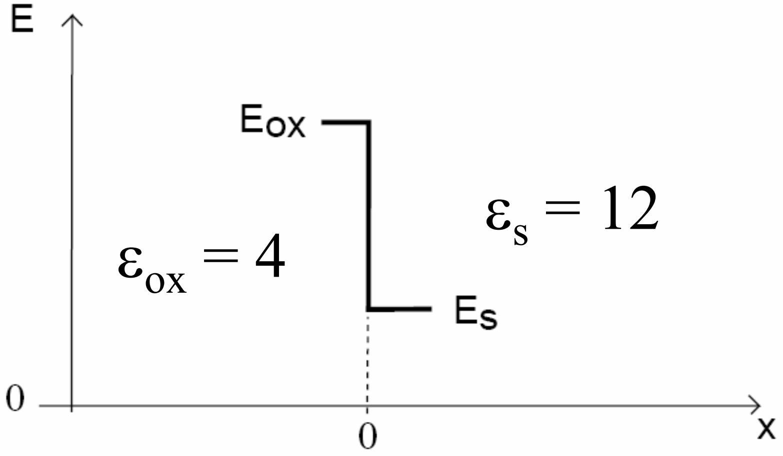


E is decreased by a factor of the dielectric constant

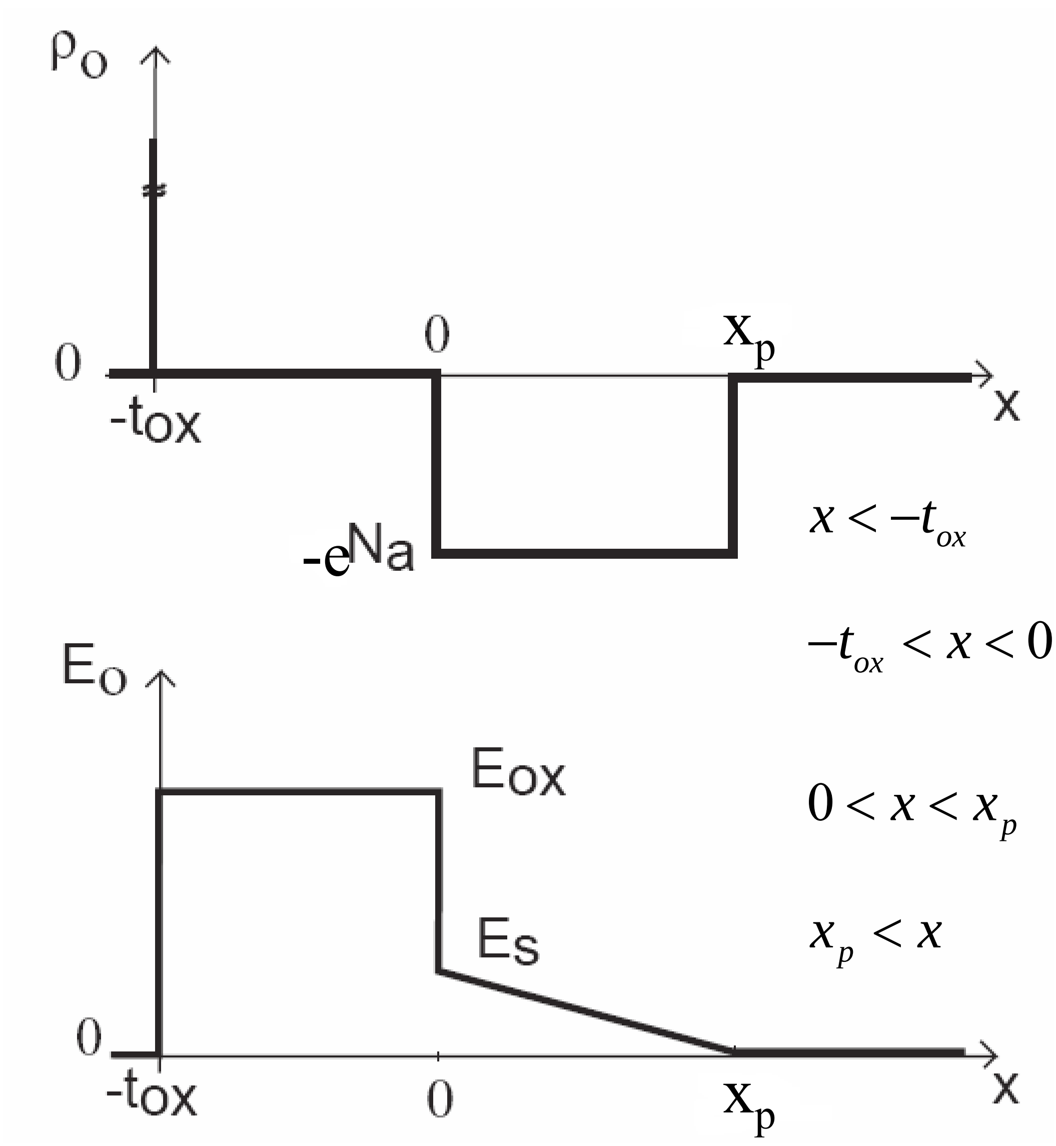
$$\varepsilon_r = \frac{E_{vacuum}}{E_{dielectric}}$$

$$\epsilon_{ox} E_{ox} = \epsilon_s E_s$$

$$\frac{E_{ox}}{E_s} = \frac{\epsilon_s}{\epsilon_{ox}} \simeq 3$$

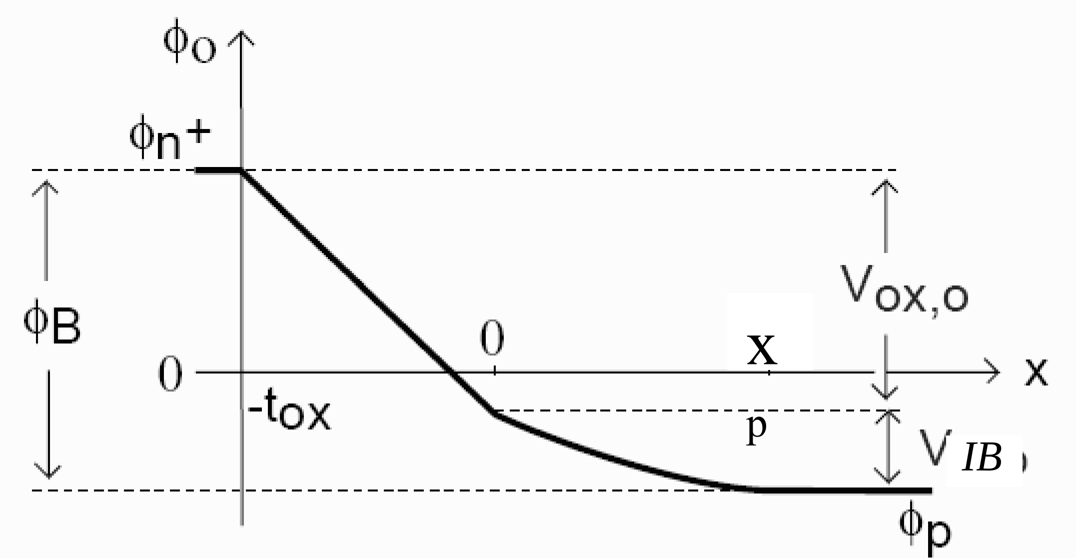


electric field



$x < -t_{ox}$	$E(x) = 0$
$-t_{ox} < x < 0$	$E(x) = \dfrac{\varepsilon_S}{\varepsilon_{ox}} E(x = 0^+) = \dfrac{eN_A x_p}{\varepsilon_{ox}}$
$0 < x < x_p$	$E(x) = \dfrac{-eN_A}{\varepsilon_s}\left(x - x_p\right)$
$x_p < x$	$E(x) = 0$

electrostatic potential



$$x < -t_{ox} \qquad \phi(x) = \phi_{gate}$$

$$-t_{ox} < x < 0 \qquad \phi(x) = \phi_p + \frac{eN_A x_p^2}{2\varepsilon_s} + \frac{eN_A x_p}{\varepsilon_{ox}}(-x)$$

$$0 < x < x_p \qquad \phi(x) = \phi_p + \frac{eN_A}{2\varepsilon_s}\left(x - x_p\right)^2$$

$$x_p < x \qquad \phi(x) = \phi_p$$

(We still don't know x_p)

Band bending at inversion

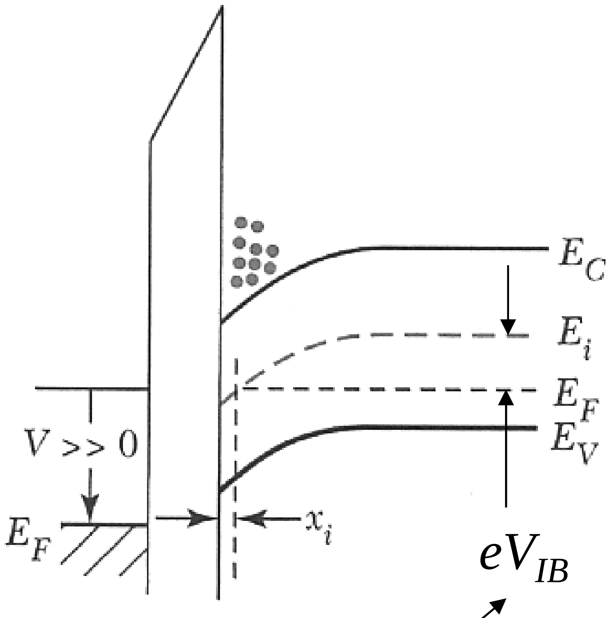
$n = N_A$ at threshold

Far on the p side

$$n = \frac{n_i^2}{N_A} = N_c \exp\left(\frac{E_F - E_c}{k_B T}\right) \qquad E_F - E_c = k_B T \ln\left(\frac{n_i^2}{N_A N_c}\right)$$

At the interface, $n = N_A$

$$N_A = N_c \exp\left(\frac{E_F - E_c}{k_B T}\right) \qquad E_F - E_c = k_B T \ln\left(\frac{N_A}{N_c}\right)$$



V_{IB} is the voltage between the interface and the body

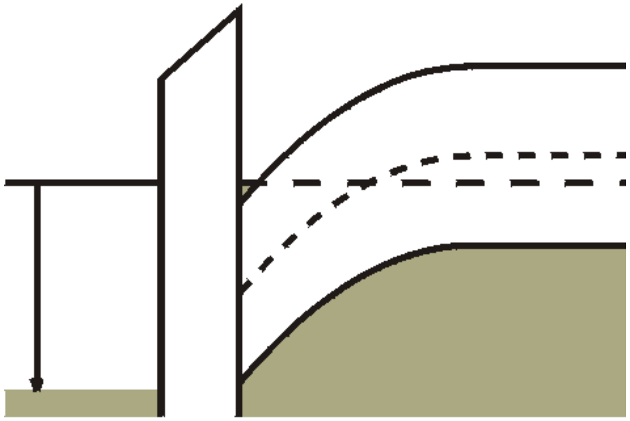
The voltage between the semiconductor-oxide interface and the body

$$eV_{IB} = k_B T \ln\left(\frac{N_A}{N_c}\right) - k_B T \ln\left(\frac{n_i^2}{N_A N_c}\right) + V_{FB} = k_B T \ln\left(\frac{N_A^2}{n_i^2}\right) + V_{FB}$$

$$\ln(a) - \ln(b) = \ln\left(\frac{a}{b}\right)$$

Strong inversion

$n_s = N_A$ at the semiconductor-oxide interface



$$eV_{IB} = k_B T \ln\left(\frac{N_A^2}{n_i^2}\right) + V_{FB} = 2k_B T \ln\left(\frac{N_A}{n_i}\right) + V_{FB}$$

The depletion width remains constant in inversion.

$$\ln\left(a^2\right) = 2\ln\left(a\right)$$

Depletion width in strong inversion

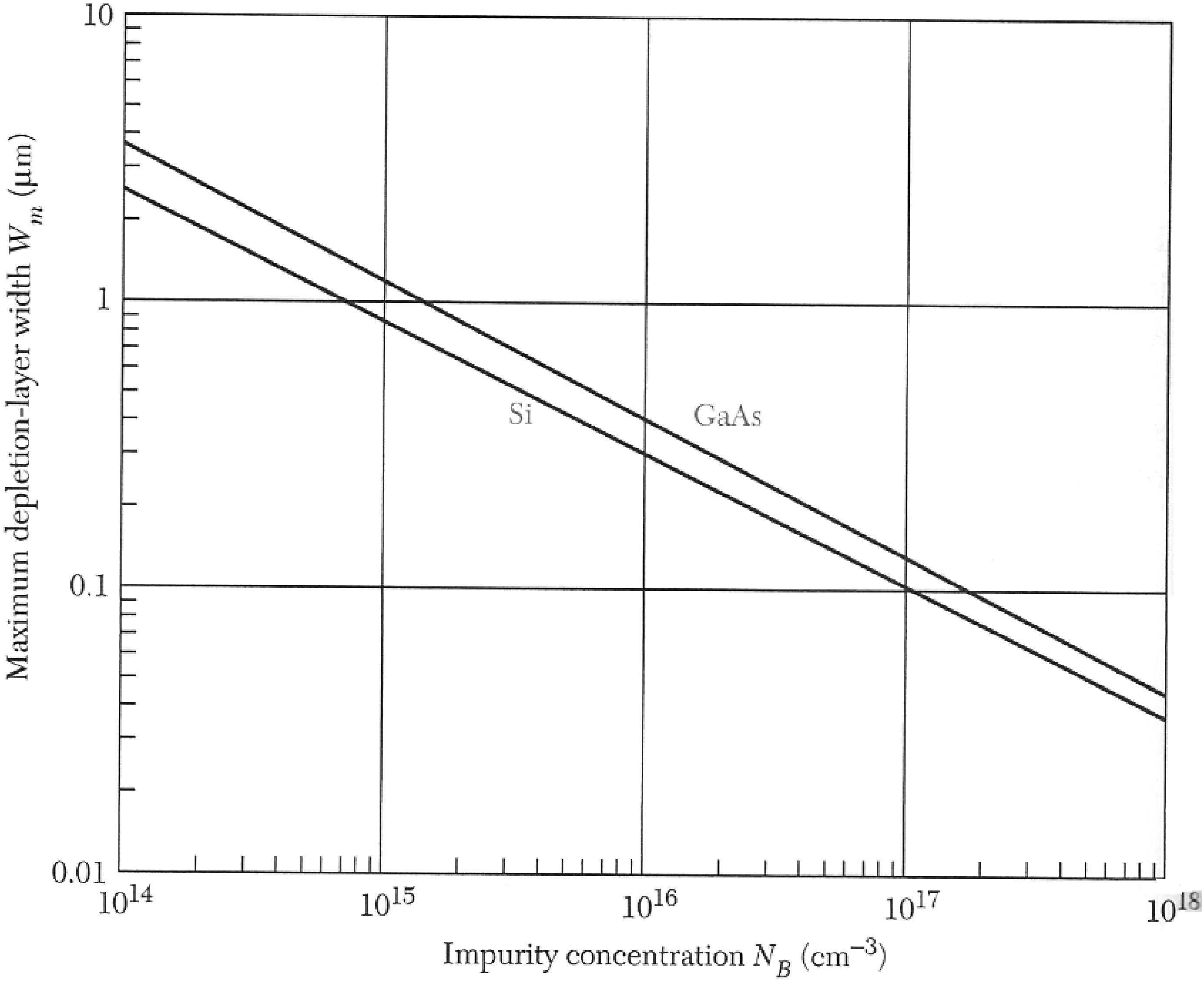
$$V_{IB} = \frac{eN_A x_p^2}{2\varepsilon}$$

$$eV_{IB} = 2k_B T \ln\left(\frac{N_A}{n_i}\right)$$

$$x_{p(\max)} = \sqrt{\frac{2\varepsilon V_{IB}}{eN_A}} = 2\sqrt{\frac{\varepsilon}{e^2 N_A} k_B T \ln\left(\frac{N_A}{n_i}\right)}$$

The depletion width remains constant in inversion.

Depletion width



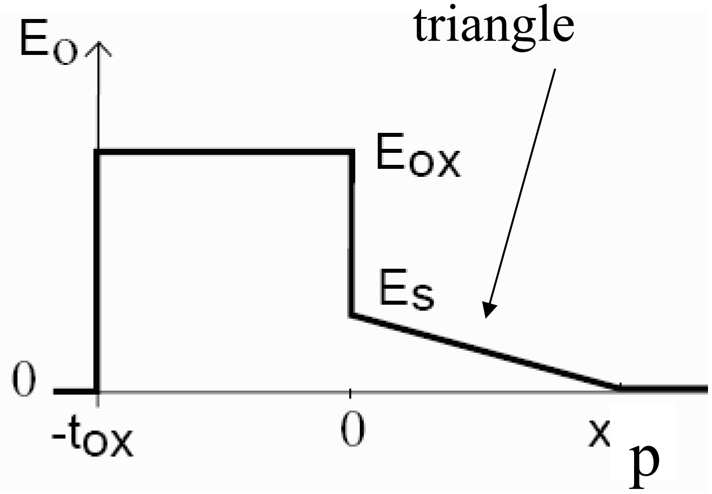
Electric field at semi-oxide interface at strong inversion

$$eV_{IB}(\text{strong inversion}) = 2k_BT\ln\left(\frac{N_A}{n_i}\right)$$

$$E_s = 2\frac{V_{IB}}{x_{p(\max)}} = \frac{2V_{IB}}{\sqrt{\frac{2\varepsilon V_{IB}}{eN_A}}} = 2\sqrt{\frac{N_A}{\varepsilon}k_BT\ln\left(\frac{N_A}{n_i}\right)}$$

$$E_{ox} = \frac{\varepsilon}{\varepsilon_{ox}}E_s = \frac{2\varepsilon}{\varepsilon_{ox}}2\sqrt{\frac{N_A}{\varepsilon}k_BT\ln\left(\frac{N_A}{n_i}\right)}$$

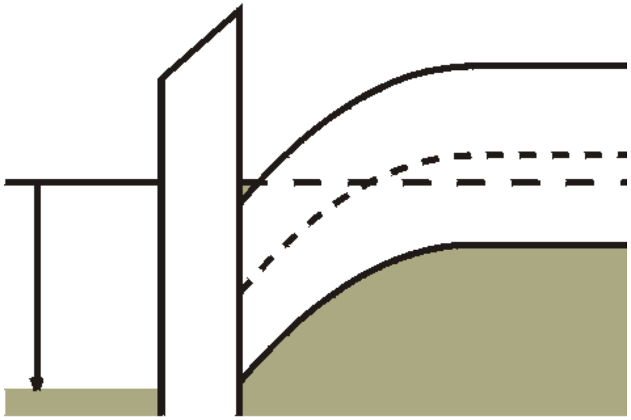
$V_{IB} = E_s x_p/2 =$ area of the triangle



Threshold voltage

$$V_T = E_{ox}\left(\text{strong inversion}\right)t_{ox} + V_{IB}\left(\text{strong inversion}\right) + V_{FB}$$

$$V_T = \underbrace{\frac{2\varepsilon t_{ox}}{\varepsilon_{ox}}\sqrt{\frac{N_A k_B T \ln\left(\frac{N_A}{n_i}\right)}{\varepsilon}}}_{\frac{\varepsilon t_{ox}}{\varepsilon_{ox}}E_{inversion}} + \underbrace{2\frac{k_B T}{e}\ln\left(\frac{N_A}{n_i}\right)}_{V_{IB}} + V_{FB}$$



Small V_T requires a small t_{ox} and a large ε_{ox}.